A HEAT FLOW MEASUREMENT SYSTEM FOR A RADIANT HEATING TEST FACILITY

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A HEAT FLOW MEASUREMENT SYSTEM FOR A
RADIANT HEATING TEST FACILITY

A THESIS
SUBMITTED TO THE DEPARTMENT OF AERONAUTICS AND ASTRONAUTICS
AND THE COMMITTEE ON THE GRADUATE DIVISION
OF STANFORD UNIVERSITY
IN PARTIAL FULFILLMENT OF THE REQUIREMENTS
FOR THE DEGREE OF
ENGINEER

By
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June 1964

ACKNOWLEDGEMENT

The author acknowledges, with gratitude, the assistance and ever-available counseling rendered by Professor W. H. Horton during the preparation of this thesis.

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SUMMARY

The heat flow measurement system obtains a temperature profile from the surface of the test structure by means of thermocouples. The thermocouple signals are used as inputs to an analogue computer which solves the appropriate heat flow equation. This computer is time shared between the 4 channels of heat control by means of a high speed stepping switch . The system is very versatile since it is independent of the source of heat. Thus it is inherently more exact than a radiation transducer system because it accounts for convective and other losses which occur in the simulation process. It has the added advantage that it can be used to measure cooling rates when the cooling results from convection as well as from radiation.

I. INTRODUCTION

The structures laboratory of the Department of Aeronautics and Astronautics at Stanford University concentrates its research in the field of thermal effects. Thus a structural test facility which includes the ability to simulate aerodynamic heating is of prime importance. The basic deterrent to a university owning and operating such a facility is that, if the facility is of reasonable size, the cost is normally prohibitive. The problem was therefore reviewed with the intention to design and construct a facility that would be economical enough for a university to own and reliable enough to get good research results. It was desired that the facility should have a capacity of a megawatt or more, and that it should be automatic in operation. It was considered essential that it should be computer controlled, and that the loop closing should be based on a measure of heat flow and not on temperature or some other property.

For a control system of this kind, it has been said that, "....(the) weak link of all methods at the present time is the assessment of the heat input. The fact that different methods are adopted for this purpose when different forms of heating are used complicates the matter still further."[1*]

How this weak link has been strengthened in the construction of a versatile heat flow measuring system compatible with most forms of heating is the subject of this thesis.

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*Superscripts refer to the reference list appended to this report.

The complete control system is functionally diagrammed in Figure 1. Simulation of the convective heat transfer from the air to the unit under test is achieved by a solution of the Newtonian equation for cooling.[2] In symbols this equation is

$$q = h(t_{aw} - t_s) + q_r - \sigma t_s^4$$

where

q = heat flux/unit area (BTU/ft^{2}hr)

h = the heat transfer coefficient (BTU/ft^{2}hr$^\circ$F)

t_{aw} = adiabatic wall temperature ($^\circ$F)

t_s = surface temperature ($^\circ$F)

q_r = total radiation pickup (BTU/ft^{2}hr)

σt_s^4 = Stefan-Boltzmann loss (BTU/ft^{2}hr)

A digital program of h , t_{aw} , and q_r (external radiation from the sun and nuclear explosion) is derived from a proposed flight profile. This program is converted to voltage signals by the digital to analogue converter. The voltage t_{aw} is combined with a voltage analogous to surface temperature in a summer and the result multiplied by h .[3] This product is added to q_r to give the desired heat flow signal, q_d . From the feedback loop the measured heat flow to the test specimen, q_m , is contrasted to q_d in a comparator. The output of the comparator, c , causes the saturable core reactors to vary the power supplied to the radiant heaters. The control loop is closed by the heat flow measurement system[4] and the correct heat flow is maintained.

Automatic operation of the facility is possible from the point at which a flight profile, programmed into digital form, is fed into a digital to analogue converter. An analogue computer receives the analogue signal from the converter and computes a command signal to adjust the power supplied to the heaters. The feedback systems then produces a signal proportional to the radiated heat absorbed by the test specimen. This signal is used to close the control loop and render the system automatic.

The Fourier equation for conductive heat flow within a body, where no convective heat flow is possible, can be combined with the principle of conservation of energy.[5] This combination for a thin block at a surface (Figure 2) subjected to a heat flux, q, is outlined below:

<u>in the x direction</u>

$$\text{heat flow in} = q(dy\,dz)dt \tag{1}$$

$$\text{heat flow out} = -K(dy\,dz)(\partial/\partial x)(T + \partial T/\partial x \cdot dx)dt \tag{2}$$

where

T = temperature

t = time

K = material conductivity

<u>in the y direction</u>

$$\text{heat flow in} = -K\,dz\,dz(\partial T/\partial y \cdot dt) \tag{3}$$

$$\text{heat flow out} = -K\,dz\,dx(\partial/\partial y)(T + \partial T/\partial y \cdot dy)dt \tag{4}$$

<u>in the z direction</u>

$$\text{heat flow in} = -K\,dx\,dy(\partial T/\partial x \cdot dt) \tag{5}$$

$$\text{heat flow out} = -K\,dx\,dy(\partial/\partial z)(T + \partial T/\partial z \cdot dz)dt \tag{6}$$

$$\text{the heat stored} = c\rho\,dx\,dy\,dz(\partial T/\partial t \cdot dt) \tag{7}$$

where

ρ = material density

c = specific capacity of the material

Combining equations for the heat in = the heat out + the heat stored and then cancelling like terms results in a simpler equation, namely

$$\rho c \frac{\partial T}{\partial t}\, dx = -K \frac{\partial T}{\partial x} - K\left(\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} + \frac{\partial^2 T}{\partial z^2}\right) dx + q \tag{8}$$

For a like block below the surface the equation is

$$\rho c \frac{\partial T}{\partial x}\, dx = K\left(\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} + \frac{\partial^2 T}{\partial z^2}\right) dx \tag{9}$$

Summing the set of equations results in

$$\rho c \int_o^{na} \frac{\partial T}{\partial x}\, dx = \int_o^{na} K\left(\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} + \frac{\partial^2 T}{\partial z^2}\right) dx + K \frac{\partial T}{\partial x}_{x=o} + q \tag{10}$$

where

n = number of divisions

a = spacing

This equation holds for a slab of material which is bounded by the upper surface of the structure and a plane parallel to that surface so long as this bound is not the lower surface of the skin. This restriction is necessary to avoid the undefinable loss from the inner surface due to radiation and convection.

Equation (10) can be re-arranged for an expression for heat flux.

$$q = \rho c \int_o^{na} \frac{\partial T}{\partial x} - \int_o^{na} K\left(\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} + \frac{\partial^2 T}{\partial z^2}\right) dx - K \frac{\partial T}{\partial x}_{x=o}$$

$$= \rho c \int_o^{na} \frac{\partial T}{\partial x}\, dx + \int_o^{na} K\left(\frac{\partial^2 T}{\partial y^2} + \frac{\partial^2 T}{\partial z^2}\right) dx - K \frac{\partial T}{\partial x}_{x=na} \tag{11}$$

The spatial derivatives $(\partial^2 T/\partial y^2)$, $(\partial^2 T/\partial z^2)$ at any level in the direction of the inward normal can be expressed in the form

$$\frac{\partial^2 T}{\partial y^2} = \frac{1}{C} \left[\alpha T_1 + \beta T_2 + \ldots \gamma T_n\right] \tag{12}$$

where C , α , β , γ ... are coefficients as reproduced in Table 1 from Reference 6.

The integrations to be made can be done by an approximation. By application of Simpson's rule for $n = 2$ equation (12) becomes

$$\frac{\partial^2 T}{\partial y^2} = \frac{1}{3a} \left[T_o - 8T_1 + T_2\right] \tag{13}$$

where the equally spaced temperatures are measured in the y-z plane as depicted in Figure 2.

Equation (11) then can be written

$$q = \rho\, cna \frac{\partial T_1}{\partial t} - \frac{K}{3a} (T_o - 8T_1 + T_2) - \frac{K}{3a} (T_o' - 8T_1 + T_2)$$

$$= C_1 \frac{\partial T_1}{\partial t} - C_2 (T_o + T_2 + T_o' + T_2' - 16T_1) \tag{14}$$

All the terms in equation (14) are directly determinable from a spatial temperature survey. The differentiation can be performed in an analogue computer as can the summations and multiplications.

The preceeding analysis outlines the method of the heat flow solution utilized in the feedback computer system for all 4 channels of control.

IV. DETAILS OF A SINGLE CHANNEL

Eighteen thermocouples are capacitance-welded to the surface of the test structure. The temperature survey used in the first channel of control appears in Figure 3. The voltages generated by the thermocouples are connected to a high-speed stepping switch which sequentially connects the voltages to the appropriate computer elements.

The analogue computer consists of a d-c power supply, 4 chopper-stabilized amplifiers, 1 differentiator, 1 summer, and 5 peak follower amplifiers. Details of these components are discussed in a later section.

To clarify the different functions of the computer, a step-by-step solution of the heating equation for channel 1 is presented (see Figure 4). T_1, as a voltage, is received on the first step by bank number 1. From bank 1, T_1 is amplified and then connected to bank 2. From here T_1 is again amplified and then differentiated.[7] The output of the differentiator is temporarily stored in capacitor, C_1. This charge is drawn from C_1 on the second step of bank 3 by peak follower 1 and then connected to summer S. Also on the second step T_1, $-T_o$, $-T_2$, $-T_o^1$, $-T_2^1$ are joined to banks 4, 5, 6, 7 and 8 respectively. These signals are summed and amplified in chopper amplifier 1. Through bank 9, the sum goes to chopper-amplifier 2, after amplification this voltage is diverted through the second step of switch 2 to summer S. This summer sums the voltages as required by equation (14). This solution, q, is switched through banks 10 and 11 to storage in capacitors C_2 and C_3. Two banks are necessary here so that the total q may be decreased as well as increased. This is done by grounding C_2 through bank 11 on the third step. Bank 12, still on the second step, diverts q through peak follower 2 to the comparator thus completing the control loop.

It should be noted that the radiation losses from the test specimen have yet to be taken into account. To compensate for this effect, it was determined that a σT_1^4 term, where σ is the Stephan-Boltzmann

constant, could be approximated by 3 straight line slopes. (For this approximation see Figure 5.) Accordingly, a biased diode circuit was devised to follow the approximation. (See Figure 6) T_1 is first amplified to a workable voltage and is then summed with a compensating voltage to make it proportional to absolute degrees Fahrenheit since σ involves absolute temperatures. The output from the summer is then admitted at the proper level by the biased diode circuit to achieve the 3 changes of slope necessary to approximate the fourth power function. It is to be noted that at smaller voltages, i.e. lower temperatures, the radiation compensating circuit is opened. At low temperatures, however; the radiation loss is negligible (Figure 5) and has virtually no effect upon the total equation. The amplified voltage output from the radiation compensation circuit is attenuated at summer S (Figure 4) to the proper level to correct q.

V. COMPONENT DETAILS

The thermocouples used were made of 28 gauge chromel-alumel wire junctioned with a bead weld.[8] Standard chromel-alumel thermocouples were found to give good response up to temperatures of 2450° Fahrenheit. Although platinum-rhodium thermocouples extended the upper temperature limit to 3100°F , it was felt that the additional expense involved was not worth the increase in temperature range.[9] The thermocouples were capacitance welded to the test surface. The entire test area, including the thermocouples, was painted black in order to minimize the amount of radiant power required. Several commercial heat resistant paints were tested and the best found to be common stove blacking. This paint was extremely resistant to heat. It was easily applied by brush and produced an even coat which unfortunately scratched readily.

A Philbrick compound regulated dual power supply was used to drive the computer amplifiers. This power supply has good stability and reliability. Its output of ± 300 volts d-c is stable to ± 100 millivolts per day.

The computer amplifiers used were either Philbrick K2X octal based plug-in amplifiers or a combination of the K2X and the K2P. The K2X's response time is 1 microsecond and has a rated drift of ± 8 millivolts per day. The input impedance of each amplifier is 100 megohms and the nominal output current is of the order of 4 milliamps. The amplification of the K2X is limited to 10 by stability criteria; consequently, K2X's were used as summers and as peak followers. A peak follower is essentially an amplifier with unit feedback. It is used in conjunction with a temporary-storage capacitor and will provide an output voltage which is the peak value of the past history of the capacitor charge. To attain higher stability when amplifying by 1000, a K2X amplifier is stabilized by a K2P chopper. Drift rates for this setup are of the submillivolt level and accuracies in the order of 0.1% are attained.

The capacitors used as storage banks are all 0.25 microfarads with a time constant of 10 microseconds. This means that the capacitor is charged to 99% of its final value in that time.

The device which enables the computer to time share its amplifiers is a type 45 rotary switch manufactured by Automatic Electric. It is a heavy duty, magnet-driven stepping switch with positive non-overthrow stepping. It can be operated by remote control pulses or by self-interruption as is done in this application. The wipers, with wiping tips at both ends (180° apart), are rotated in one direction over a semicircular arrangement of 12 banks of 25 contacts each. The first 3 banks are gold plated and are used in the differentiator circuit where the decrease in noise level is of prime importance. The switch is driven by a 24 volt d-c power supply to step at 56 times per second. Since the wiper is double ended, each contact is scanned at a rate of 112 times a second. Dwell time on a contact is 6.4 milliseconds or 80% of the time for each step. The switch is so wired as to complete the computations for one channel in 3 steps. The fourth step begins channel number 2 computations and so on in sequence. Since the switch contains 25 steps, the channels are scanned 4 times for each revolution of the switch wipers.

VI. CONCLUDING REMARKS

The heat flow measuring system incorporated into the radiant heating structures testing facility has the primary advantage of being independent of the source of heat. It can be used to measure heat flux in systems utilizing convection, radio frequency induction, or radiant heating methods. It also can be used to measure heat flow in the cooling phase of a flight profile which could produce serious thermal transients comparable to those in the acceleration phase.

Experiments with the heat flow measuring system described in this thesis were so successful that it was decided to extend the system of control to include the deceleration as well as the acceleration phases. For this purpose, it is essential to introduce some form of cooling in addition to radiant cooling. After due deliberation, it was considered that the most successful means of additional cooling would be to blow cold gas onto the surface of the specimen. It was decided that liquid nitrogen would provide the best heat sink; and as a consequence, the heater arrays were adapted to include cooler arrays (see Figure 7). These cooler arrays consist of a series of quartz tubes identical in character to the envelopes of the infra-red lamps. They were placed in a plane parallel to that of the heater lamps and had slots and holes along their lower surfaces. Through these tubes was blown cold nitrogen from a gas generator integral with the reflector. This arrangement did not interfere in any way with the passage of the radiant heat to the specimen since the quartz tubes of the cooler array transmitted the radiation with no loss of efficiency. The presence of the heat exchanger in association with the reflector surface gives two distinct advantages: first, the cold fluid is conveyed as near as possible to the test specimen in the form of a liquid and second, the cooling of the reflector itself makes it possible to use intensities of infra-red not practical without this feature. In order that the system of regulation should not require additional servos for the cooling case, overcooling was used and the balance of heat adjusted by

means of the infra-red system. Further developmental work along these lines is clearly desirable, but it seems quite certain that the feasibility of such a method has been established.

A second advantage, often of the greatest importance, is that the system can be economically constructed from standard components. [illegible]cial transducers are needed to measure the heat flow.

REFERENCES

1. Horton, W. H., "The Simulation of Heat and Load Environment in High Speed Vehicles," Engineer's Thesis, Stanford University, June, 1957.

2. Chapman, A. J., "Heat Transfer," MacMillan Publishing Company, New York, 1960.

3. Geronime, E. L., "A Digital to Analogue Computer Control For Use in an Aerodynamic Heating Simulation System," Engineer's Thesis, Stanford University, August 1962.

4. Campbell, J. D., "A Feedback System For Automatic Control of Simulated Aerodynamic Heating," Engineer's Thesis, Stanford University, August 1962.

5. Fourier, J., "The Analytical Theory of Heat," University Press, London, 1878.

6. Southwell, R. V., "Relaxation Methods," Oxford University Press, 1940.

7. Horton, W. H. and Steel, C. E., "Analog Differentiation For Control Systems," SUDAER No. 166, Stanford, August 1963.

8. White, F. J., "Accuracy of Thermocouples in Radiant-Heat Testing," Experimental Mechanics, July 1962.

9. Roeser, W. F. and Wensel, H. T., "Methods of Testing Thermocouples and Thermocouples Materials," National Bureau of Standards, Washington, D. C.

BIBLIOGRAPHY

1. Wass, C. A. A., "Introduction to Electronic Analogue Computers," Pergammon Press Ltd., London, 1955.

2. Horton, W. H., "The Influence of Kinetic Heating on the Design and Testing of Aircraft Structures," Conference on High-Speed Aeronautics, Polytechnic Institute of Brooklyn, January 1955.

3. McAdams, W. H., "Heat Transmission," McGraw-Hill, New York, 1954.

4. Horton, W. H., "Experimental Methods in Kinetic Heat Tests," Aircraft Engineering, Volume XXIX, Number 342, August 1957.

5. Loria, J. C., More, J. W., and Blackstock, W. J., "The Design and Application of the M. I. T. Radiant Heating Structural Test Facilities," Proceedings of the Society For Experimental Stress Analysis, Volume XV, Number I, 1957.

6. Herzfeld, K. F., "Relaxation of Partial Temperatures," The Catholic University of America, 1955.

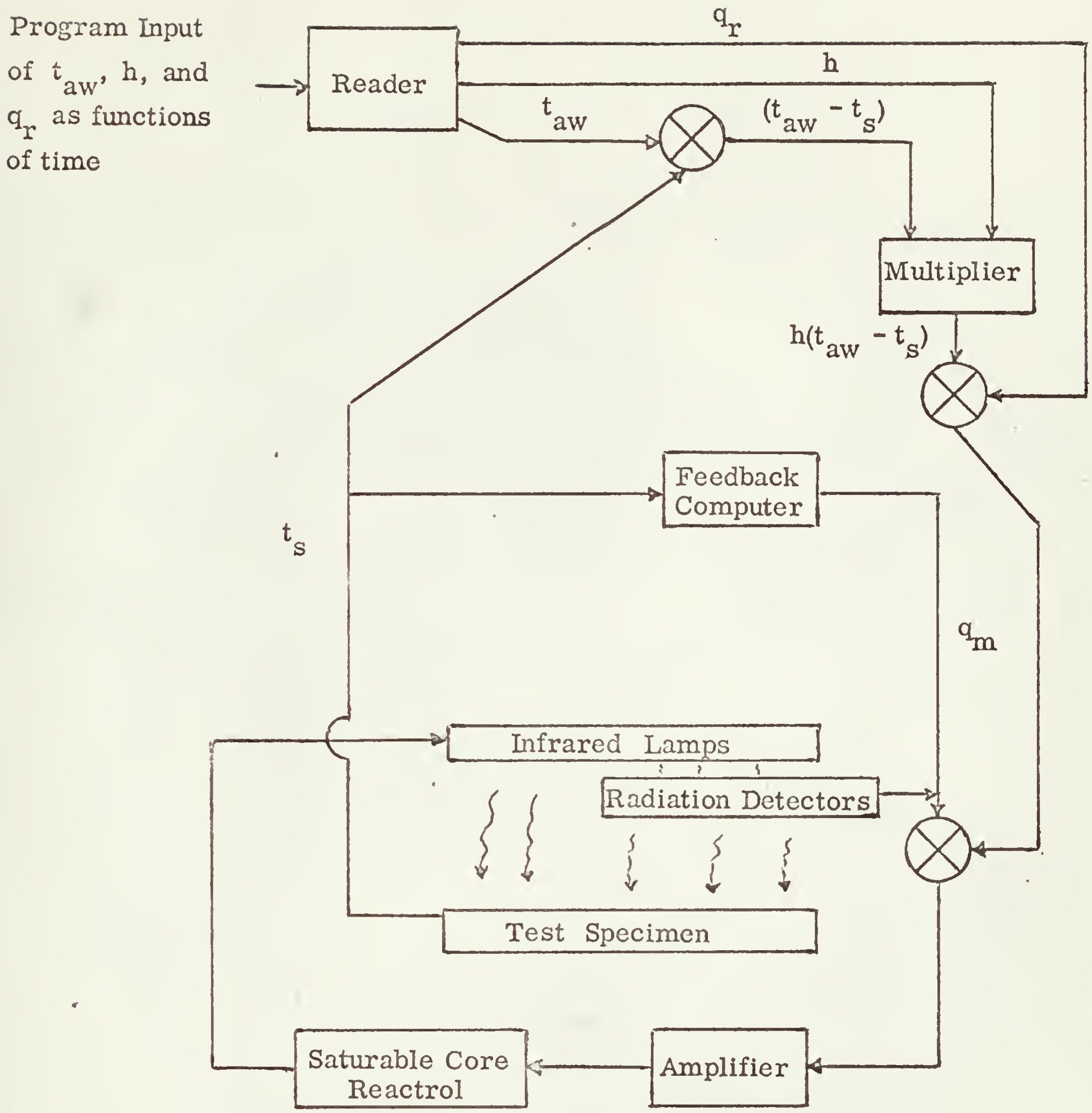


FIGURE 1

BLOCK DIAGRAM OF THE RADIANT HEATING FACILITY CONTROL SYSTEM

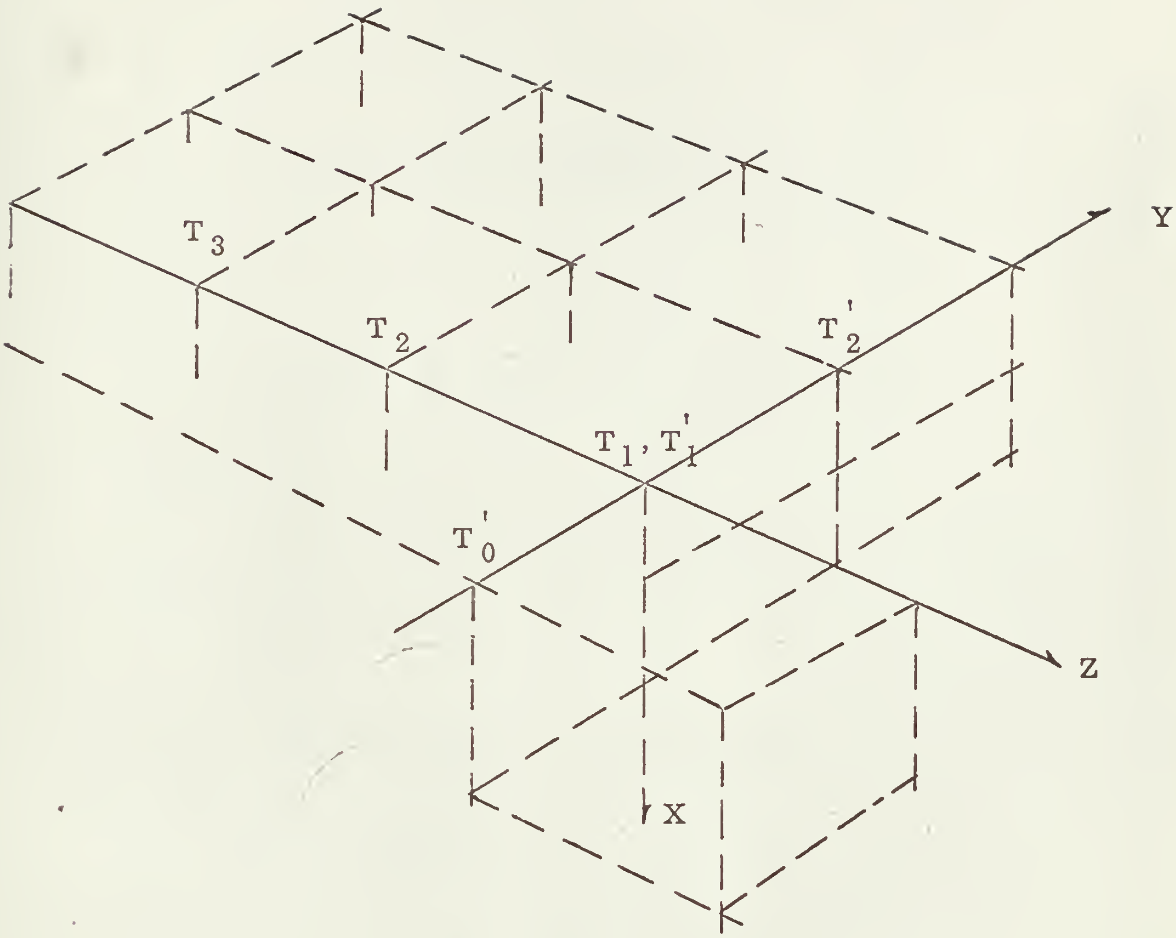


FIGURE 2

SYSTEM OF TEMPERATURE MEASUREMENT

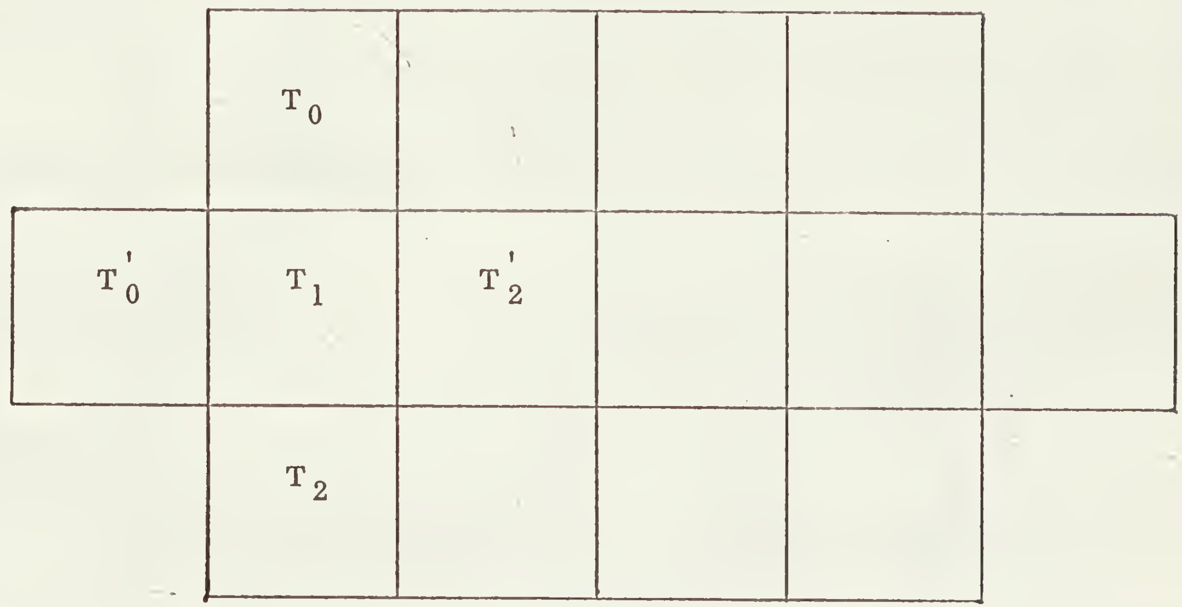


FIGURE 3

TEMPERATURE SURVEY PATTERN

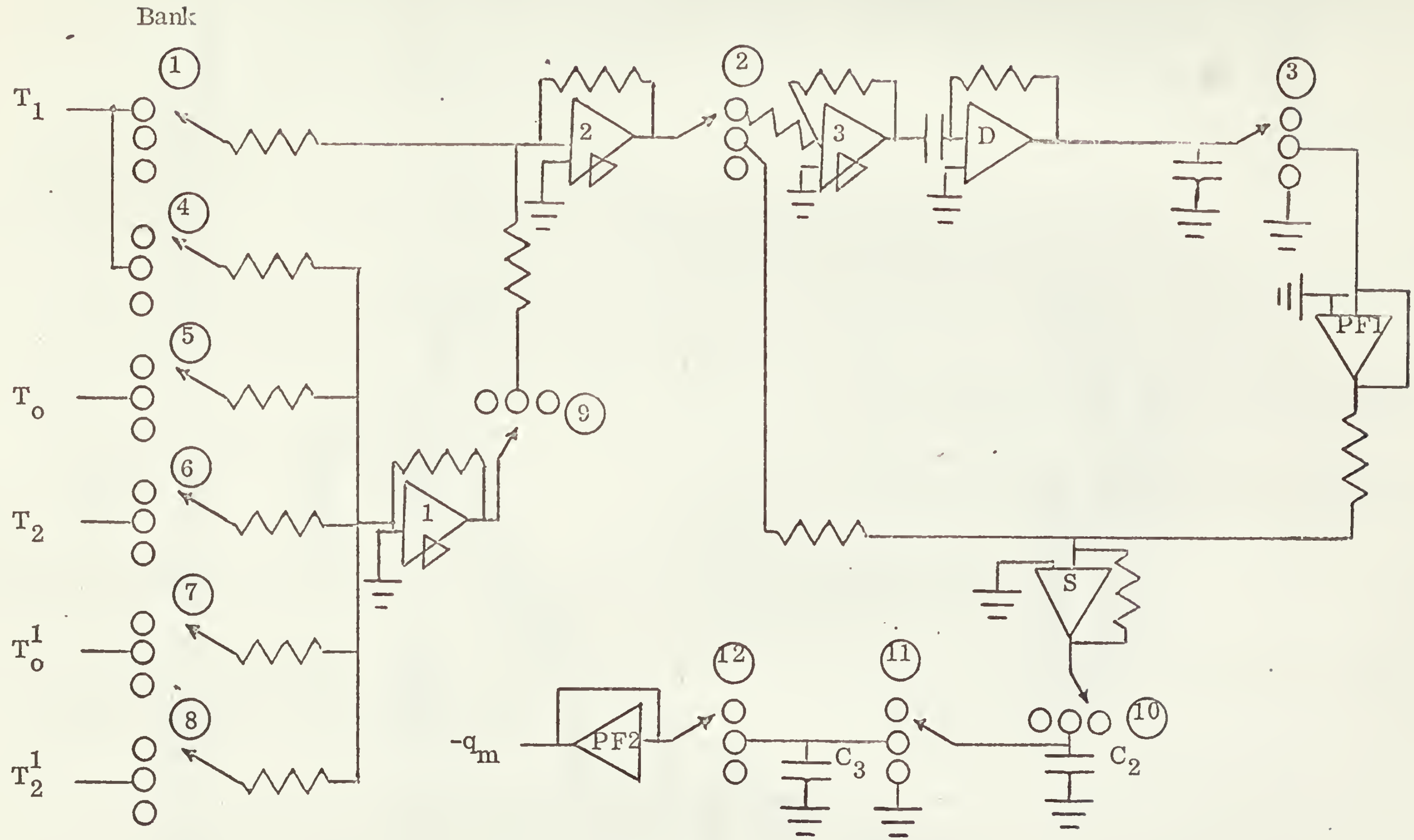


FIGURE 4

HEAT FLOW MEASUREMENT SYSTEM FOR CHANNEL 1

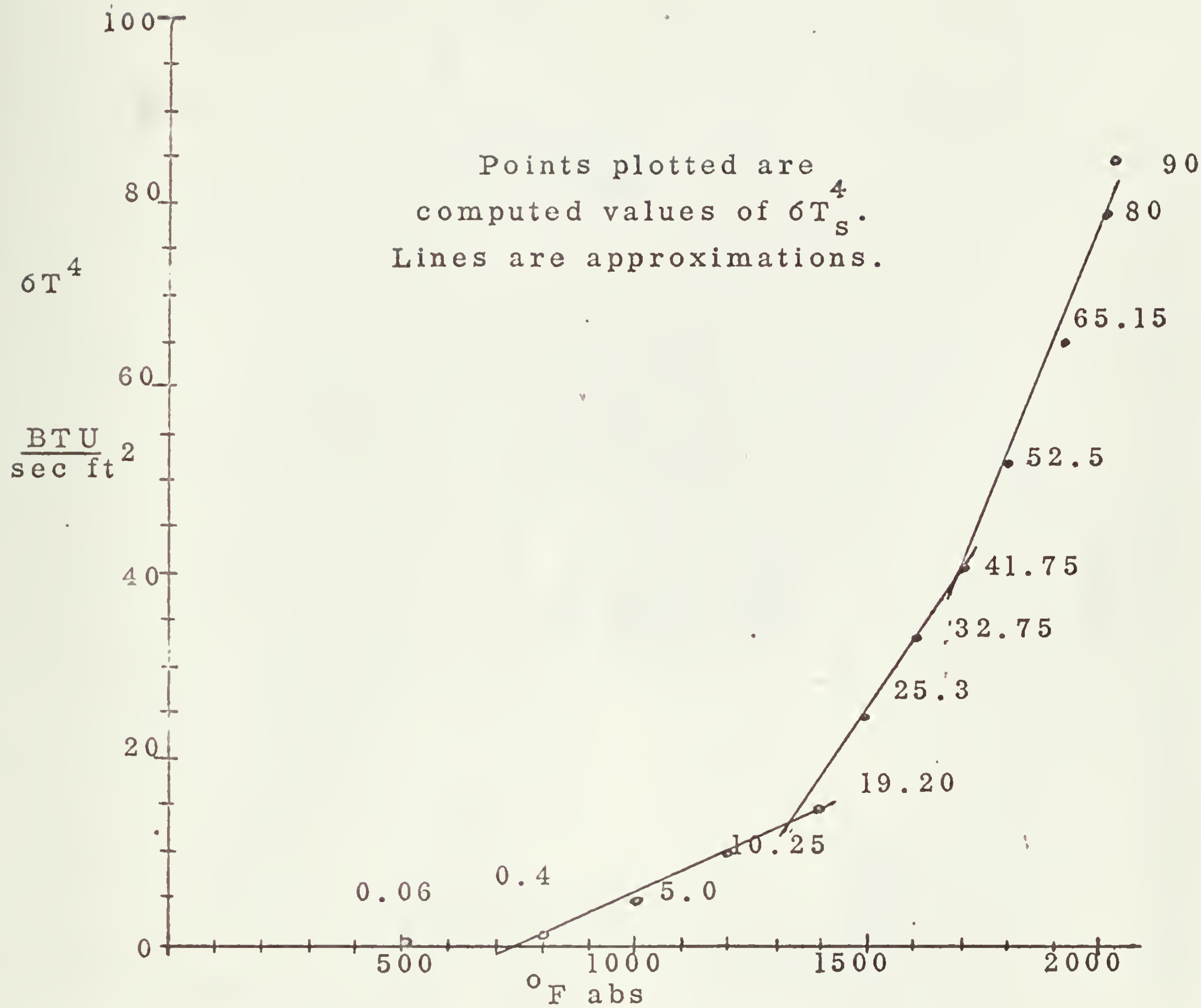


FIGURE 5

APPROXIMATION OF THE RADIATION LOSS CORRECTION

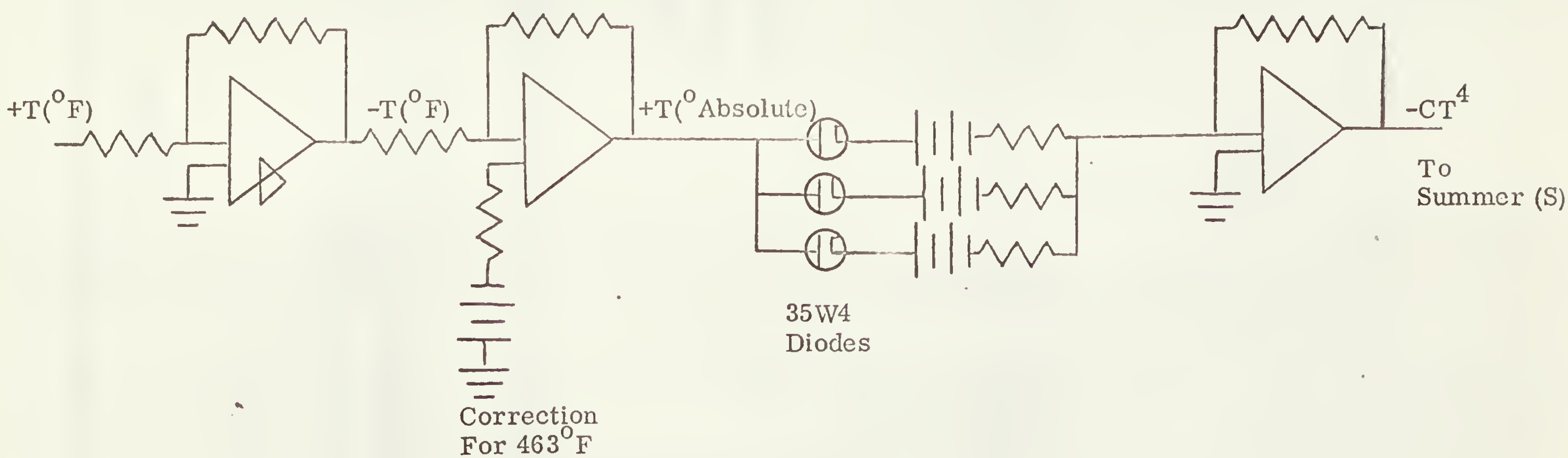


FIGURE 6

BIASED DIODE CIRCUIT TO CORRECT FOR RADIATION LOSSES

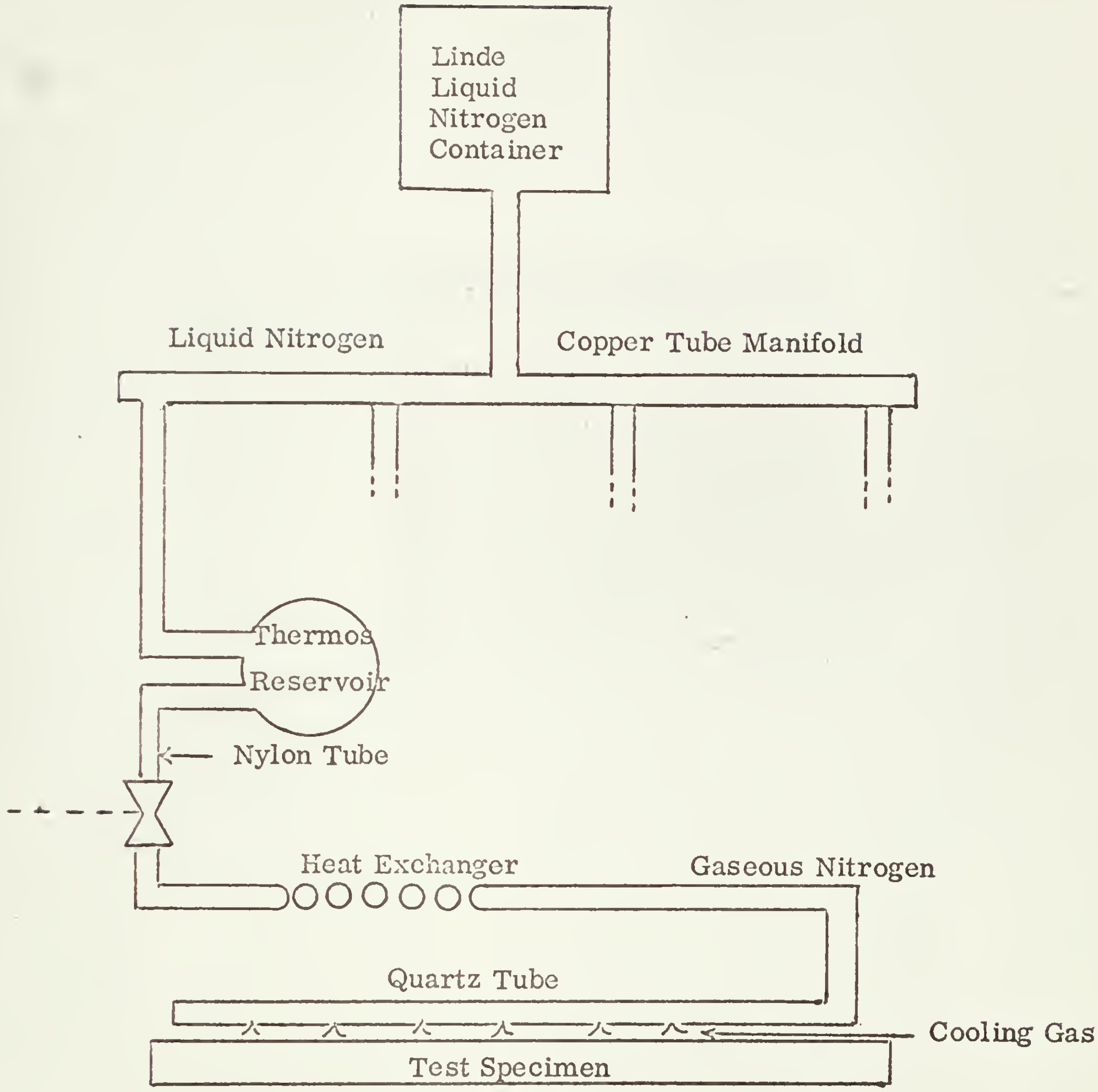


FIGURE 7

DIAGRAM OF THE COOLING PHASE SIMULATION

APPENDIX A

THE CALORIMETER AND TEST DATA

THE CALORIMETER AND TEST DATA

For calibration of the transducers, a calorimeter was made from stainless steel. It consisted of a 1/32 inch thick disc, 3/4 inch in diameter. A diagram of the calibration equipment is given in Figure A1. The calorimeter was guarded along its edge by a ring of the same material and on its rear face by another disc. In this way the heat losses from the calorimeter were made negligibly small. This was verified by recording thermocouples attached to various points on the rear face of the calorimeter. The temperature of the disc was found to rise uniformly when subjected to a radiant field. A series of temperature versus time records was made for the calorimeter in the uniform field. (See Figure A2 for a picture of the test arrangement.) The tests were performed with the calorimeter at the same distance from the source that a test structure would normally be located. A radiation transducer was mounted in its normal position on the heater array used for the test. The output of the transducer was recorded simultaneously with the calorimeter temperature. The result of each test was thus a transducer output which corresponded to the calculated heat absorption rate. During actual structural test, the same transducer signal will represent the same heat absorption rate by the test structure. One transducer was fully calibrated in this manner and the others calibrated against this one.

Figures A3 and A4 are recordings that show the ability of the thermocouple system to produce the identical results from the same inputs on different runs at different times.

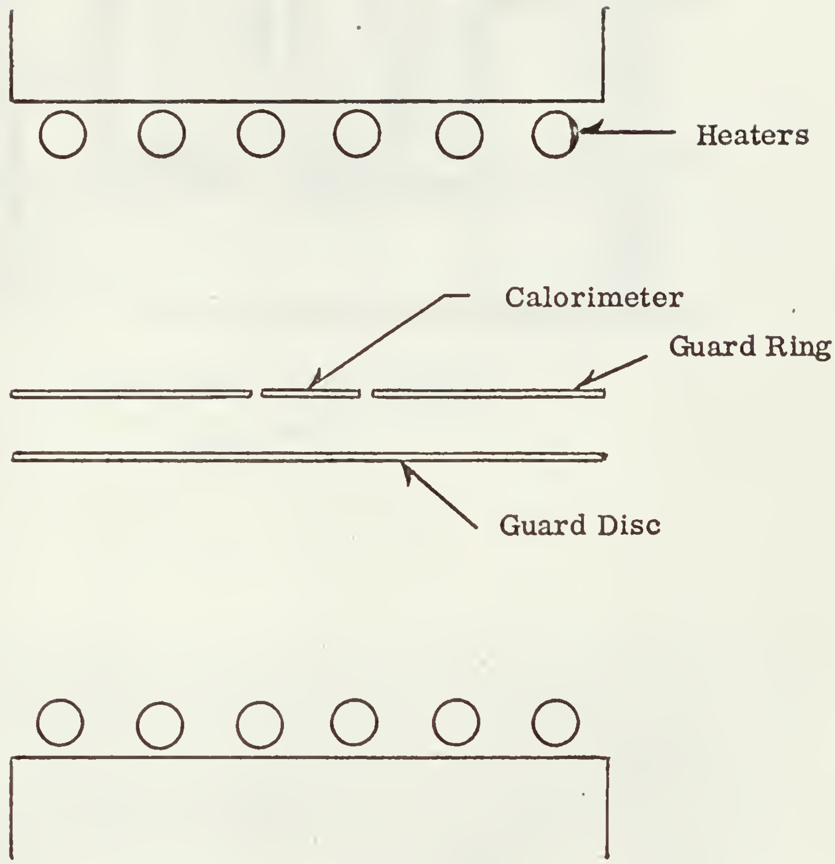
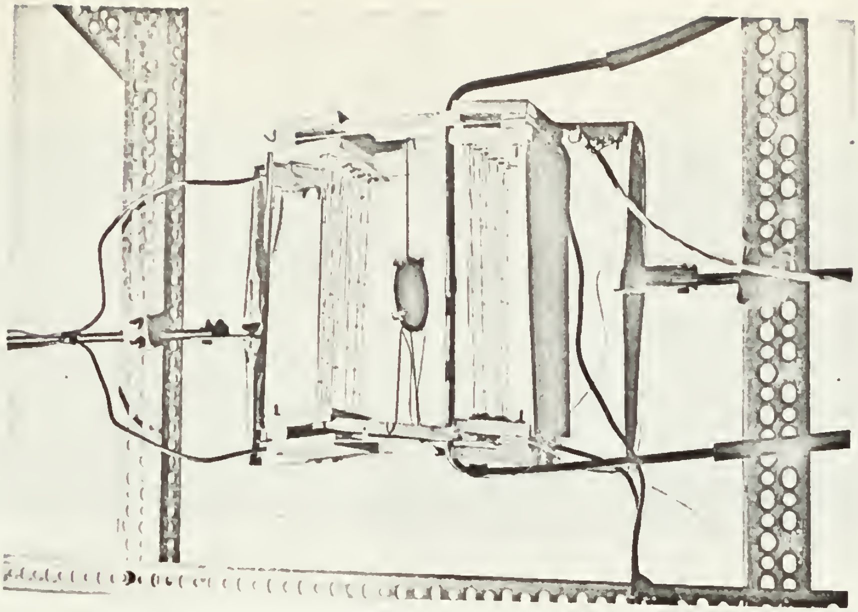


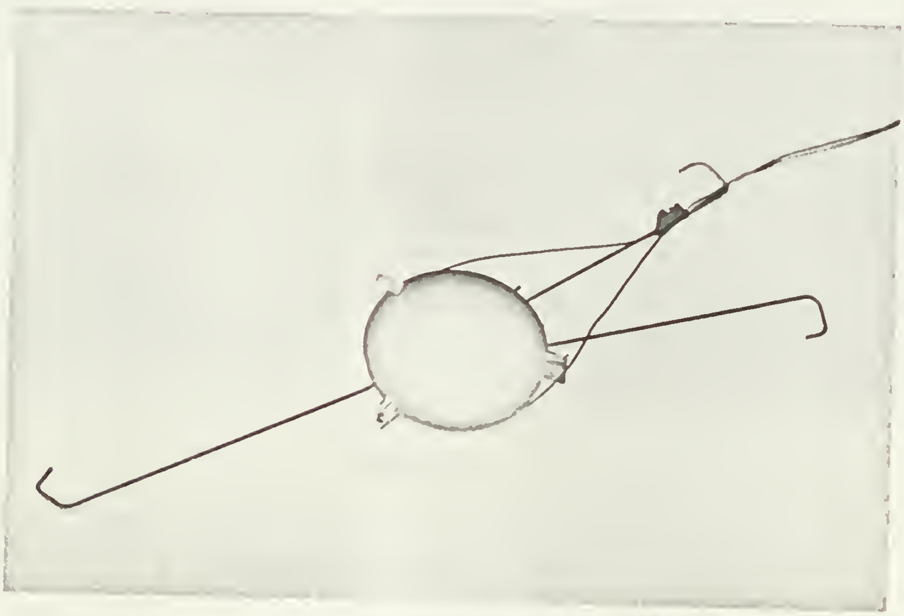
FIGURE A1

CALORIMETER TEST RIG



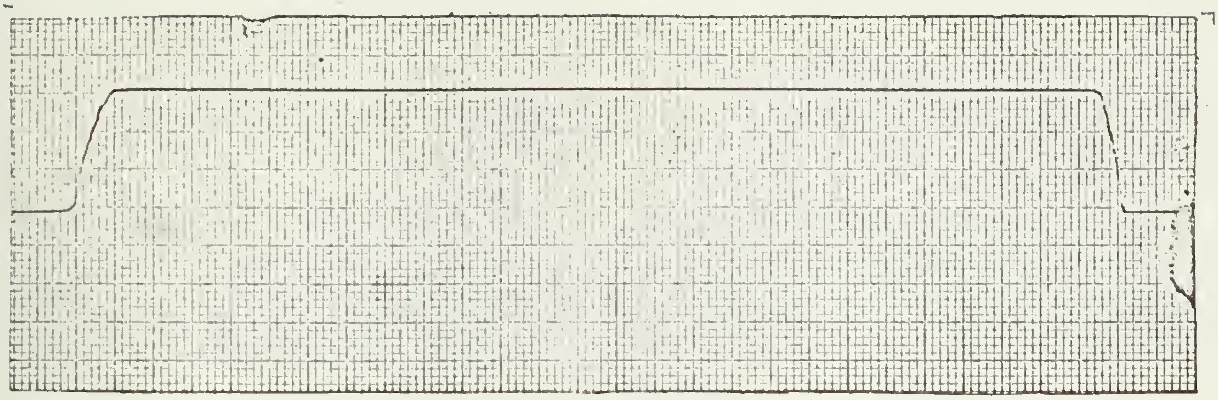
Calorimeter Test Equipment

Fig. A-2a

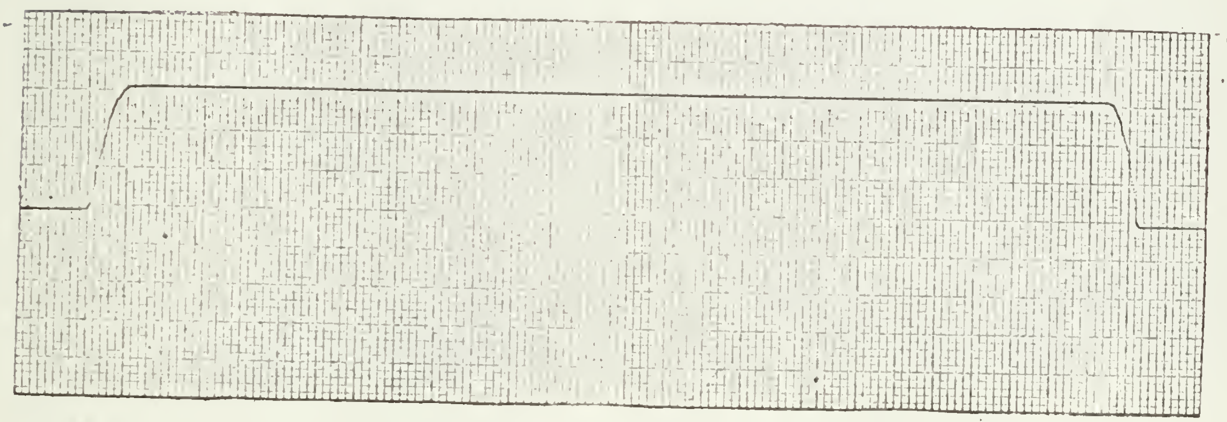


Calorimeter

Fig. A-2b



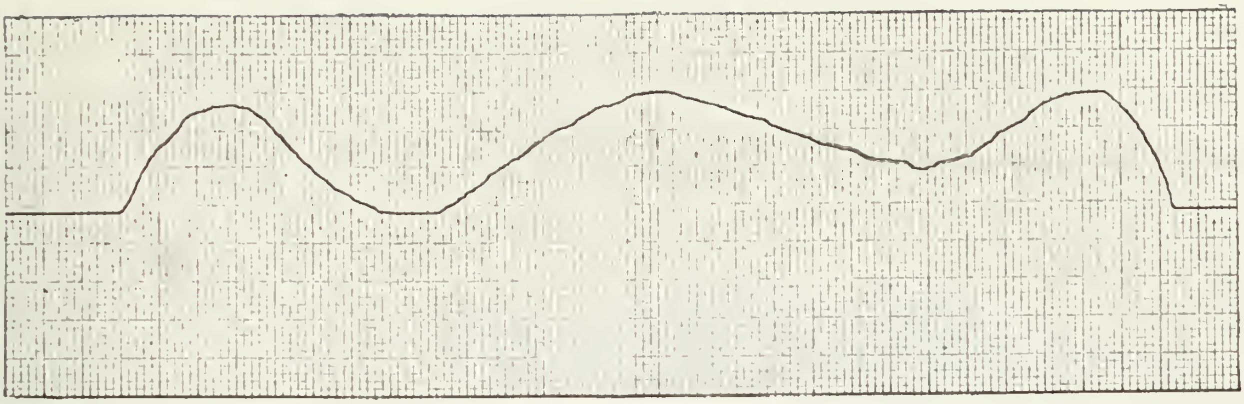
Run 1



Run 2

CONSTANT RADIATION

FIGURE A 3



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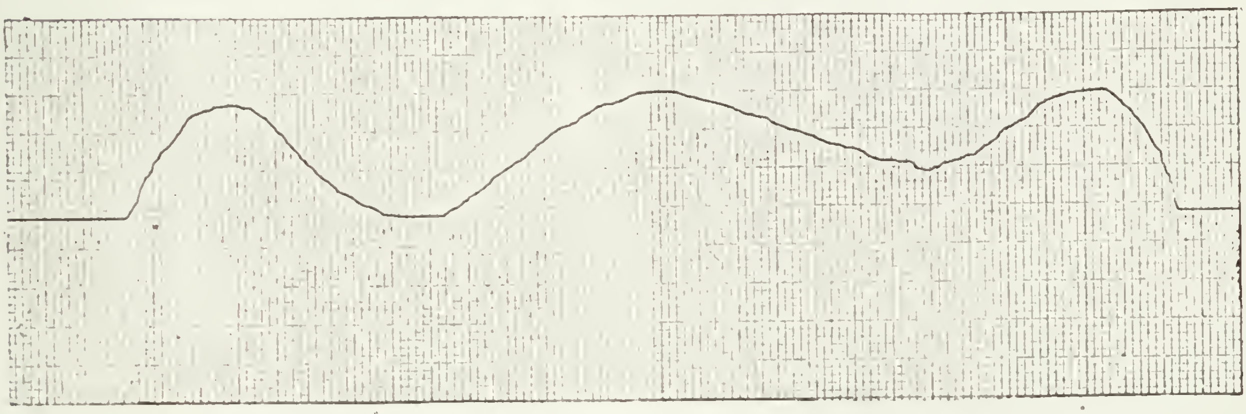

Run 2

VARYING RADIATION
FIGURE A 4

APPENDIX B

STANFORD UNIVERSITY RADIANT HEATING
STRUCTURAL TEST FACILITY

by

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APPENDIX B: STANFORD UNIVERSITY RADIANT HEATING STRUCTURAL TEST FACILITY

I. INTRODUCTION

The need for aerodynamic heat simulation in structural testing of supersonic aircraft is well recognized. Thus, the authors undertook the design and construction of a four channel radiant heating test facility at Stanford University during the summer of 1962. The system was designed to meet the following requirements: a high intensity, rapid response heat source; an adequate reflector system to direct the heat; an absorptive finish on the test specimen to permit maximum utilization of available heating power; a practical technique for surface temperature determination; a system of radiation measurement; and a computer control system to correctly vary the heat input to the test specimen.

II. SYSTEM LOGIC

Figure B-1 is a block diagram of the control system for the radiant heating test facility. Voltages analogous to h and t_{aw} are generated and then utilized by the computer along with a voltage analogous to t_s for solution of the Newtonian convective heat transfer equation, $q = h(t_{aw} - t_s)$. Another voltage (q_r) representing radiation from external sources (sun, atomic blast, etc.) is generated and then added to q in a summing circuit to give the desired heat flow signal, q_d. The comparator output, c, is the difference between q_d and q_m, the measured heat flow. The control signal causes the power regulating device to vary the power supplied to the heaters. The heat flow measurement system closes the control loop, causing the correct heat input to the test structure to be maintained. The measurement of heat input to the test specimen is made by either of two systems. The operational details of these devices are explained briefly in Section III and in detail in References [1] and [2].

III. SYSTEM DETAILS

Certain requirements are essential in a practical feedback control system for the simulation of aerodynamic heating. The requirements set for this facility are to:

(1) accurately compute desired heat flows for simulation of speeds up to Mach 6.

(2) be capable of measuring the heat inputs to the test specimen.

(3) be dependable.

(4) be safe to operate.

(5) be inexpensive as possible.

(6) be simple to operate and program.

The operations of the function generator and computer shown in Fig. B-1 are combined in the digital to analogue computer control system. This unit consists of a punched tape reader, an operational amplifier and resistance bank, two peak followers and associated capacitors, a multi-bank stepping switch, a summer, and a chopper stabilized amplifier. (Fig. B-2) The details of the individual components are given in Reference [1] and only the modus operandi is discussed here.

Values of h and t_{aw} are obtained from the Stefan-Boltzmann law. A binary coded program of these time dependent functions is made on a punched tape. This tape is placed on a reader and used in the time shared system as follows: an analogue voltage proportional to q_r is generated from a resistance network and a reference voltage in conjunction with an operational amplifier. This signal is temporarily stored. The next command is t_{aw} which is treated in the same way. The output of the temperature transducers, t_s, is amplified by a chopper stabilized amplifier and then subtracted from the stored t_{aw} analogue in a summer. The voltage difference $(t_{aw} - t_s)$ is used as the reference voltage for the next stage of the operation. This consists of giving the command, read h, and by virtue of the fact that the reference voltage is analogous to $(t_{aw} - t_s)$ the output of the system is analogous to the product $h(t_{aw} - t_s)$. Simultaneously, q and q_r are added in a summer and this voltage, analogous to q_d, is stored in a capacitor. These steps are repeated for channels two, three, and four. The digital to analog computer evaluates a new value of q_d for each channel every 1.2 seconds. Thus, by time sharing, by digital to analog conversion, and by unique computer techniques,[1] a simple and accurate means for obtaining a q_d history is realized.

There are two systems available for closing the control loop. Both systems measure the rate of heat flow to the test specimen and therefore may be used interchangeably. One system, the classic system, consists of special transducers. These essentially consist of thermocouples in conjunction with substantial heat sinks. In a radiant field the thermocouples reach an equilibrium temperature proportional to the radiant intensity. Each transducer is two thermocouples connected so that their signals oppose. One is subjected to the radiation from the heaters and the other to the reflected radiation. The output is therefore proportional to the difference between the incident and reflected radiation. This is q_m exclusive of convective losses. The heat sinks for the transducers are cooled metallic blocks. The instruments are attached directly to the sides of the heater arrays. They are calibrated in a calorimetric manner.

The other system, one especially devised for this project, consists of eighteen thermocouples arranged to obtain temperature profiles in the test specimen. A high speed stepping switch sequentially connects the thermocouple signals to an analogue computer which solves the appropriate heat flow equation. The computer is time shared by the 4 stations. The latter system is more versatile than the former since it measures net heat flow irrespective of the nature of the source. Thus convective losses in simulation are accounted for. An additional refinement to the computer permits compensation for radiant losses which the structure would normally experience in flight. Figure B-3 is a photograph of the feedback computer system.

Voltages in the control system are scaled such that at any time the prescribed q_d level is twice the anticipated q_m level. A summing circuit subtracts q_m from q_d and the output (c) is used to control the power regulating devices. Due to the two-to-one scaling the control signal consists of a set-point voltage plus an error voltage. Thus, the heaters are controlled in such a manner that the desired and actual heat inputs are equalized. This occurs when the error voltage level converges to zero and the control signal converges to the set-point voltage.

Main power is supplied through two 300 KVA, 480 volt, 3 phase, General Electric transformers. The power regulating devices consist of 75 KVA, 480 volt, 3 phase General Electric saturable core reactors and

their associated control units. Transient operation of the power equipment on an overload duty cycle makes possible peak outputs of two to three times rated value. Heating capacity of more than one megawatt is therefore feasible. Figure B-4 is a photo of the saturable core reactor units.

The basic heating elements are General Electric T.3 infra-red lamps. (See Fig. B-5) They consist of a tungsten filament supported by tantalum disc spacers in a sealed quartz tube 3/8 of an inch in diameter and 12 inches in length. Each unit is rated at 1000 watts at 220 volts. They are capable of withstanding the 480 volt peak output of the power supply and under these conditions develop approximately 3 kilowatts.

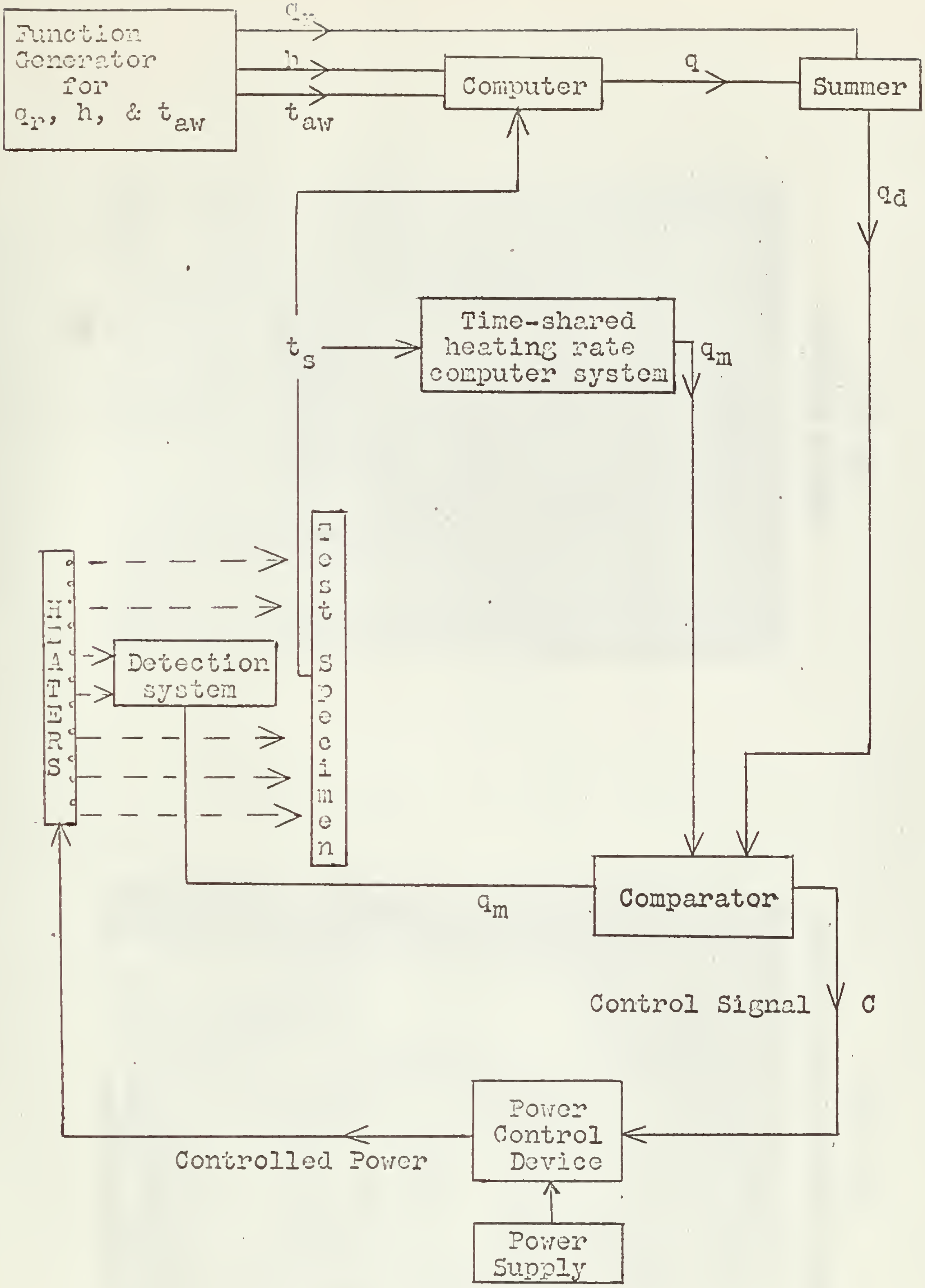
The heaters are arranged in groups of six. Figure B-6 is a photograph of one such unit. The heater arrays are connected in delta to the three phase power from the saturable core reactors. Each unit covers about one third of a square foot. Thus, the maximum radiant intensity possible with the present arrangement is about 60 kilowatts per square foot. Two thousand watt heaters of the same external size are available when higher intensities are required. Peak output of these is 6000 watts per heater. The heater arrays are quite adaptable and may be bolted to any suitable frame to surround a test structure. Special arrangements may easily be devised for special purposes, such as the heating of curved surfaces.

Figure B-7 shows an overall view of the test facility. The main items of equipment and the channels of information flow are outlined on the photograph. All control, computing and recording equipment is located in the control room. This room is on the second floor of the laboratory overlooking the test site. Large windows provide for visual observation of the structure under test. The remote location of the control room was dictated by safety considerations and provides a convenient, compact center for operation of the entire facility.

IV. CONCLUDING REMARKS

The design, construction, and operation of this test facility has proved that the concept of component time-sharing is practical in certain types of control systems. It is concluded that such time-sharing is an

economical proposition in which savings in equipment costs are balanced against slightly reduced system performance. The facility is such that it can be readily installed in any small research laboratory where cost is of prime importance.

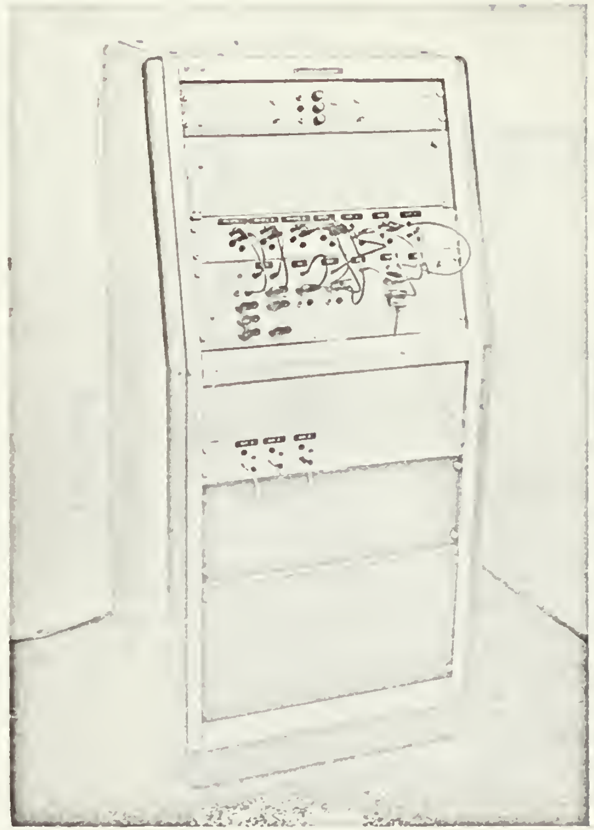


Block Diagram of a Closed Loop Control System for the Simulation of Aerodynamic Heating

Fig. B-1

Digital to Analog Computer Control

Fig. B-2



Feedback Computer

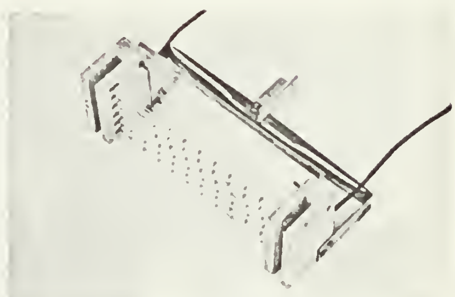
Fig. B-3

Saturable Core Reactors

Fig. B-4

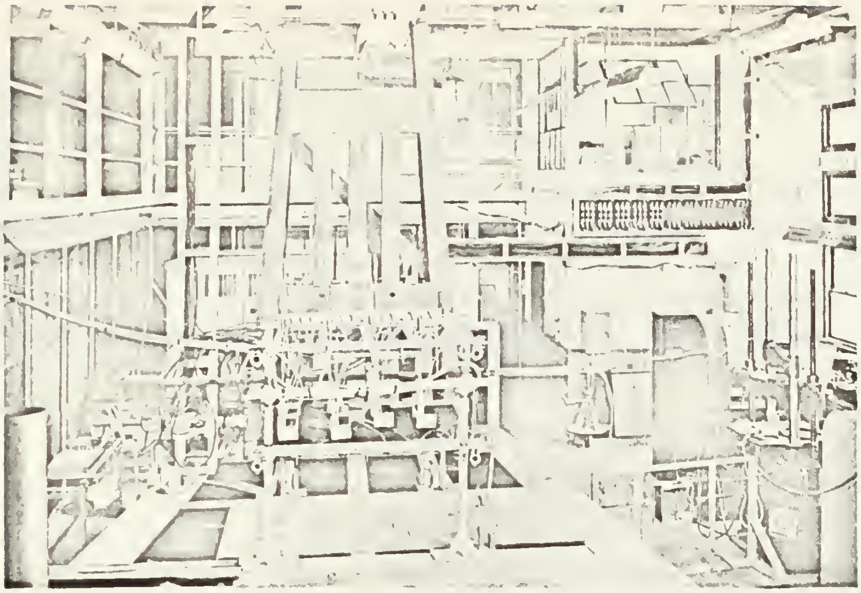
Infra-Red Heater

Fig. B-5



Heater Array

Fig. B-6



Overall View of Test Facility

Fig. B-7

Control Room

Fig. B-8

APPENDIX B REFERENCES

1. Geronime, E. L., A Digital-Analog Computer Control for Use in an Aerodynamic Heat Simulation System, Engineers Thesis, Stanford University, Stanford, California, 1962 August.

2. Campbell, J. D., A Feedback System for Automatic Control of Simulated Aerodynamic Heating, Engineers Thesis, Stanford University, Stanford, California, 1962 August.

3. Watson, R. M., A Heat Flow Measurement System, Engineers Thesis, Stanford University, Stanford, California, 1962 August.